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ANALYTICAL INVESTIGATION OF THE EFFECT OF WATER INJECTION ON SUPERSONIC TURBOJET-ENGINE - INLET MATCHING AND THRUST AUGMENTATION

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Cleveland, Ohio

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SUMMARY

An analytical investigation of the effectiveness of water injection for engine-inlet matching and thrust augmentation was made at Mach numbers from 1.5 to 2.0. One-dimensional equations for complete evaporation in a constant-area channel were applied to a fixed-geometry inlet, and its flight performance was compared with bypass and translating-spike inlets.

No-spillage engine-inlet matching was achieved over the Mach number range studied with maximum liquid-air ratios of about 0.03. Augmented thrust due to injection ranged from 17 to 56 percent higher than that of the best performing variable-geometry inlet. However, the specific impulse (thrust/(lb)(sec of liquid consumption)) of the water-injection inlet configuration was considerably lower than that of the bypass inlet and about equal to that of a fixed-geometry configuration without water injection. The total liquid consumed by the water-injection system, at matching, was one-half to two and one-half times greater than the bypass inlet configuration.

Because of the cooling effect on the air entering the turbojet engine, it was found that the maximum allowable flight speed of a temperature-limited turbojet engine (Mach 2.0 in tropopause) could be increased by 25 percent, while the cruise altitude of the bypass inlet system could be increased from 55,000 to 60,000 feet and for a fixed inlet, from 55,000 to 67,000 feet.

INTRODUCTION

High-speed aircraft operating at supersonic speeds with fixed-geometry inlets spill large amounts of air when the inlet capacity exceeds that required by the engine. This condition imposes high drags upon the airplane. In order to provide engine-inlet matching to prevent such mass flow spillage and the attendant drags, much mechanical complication has been introduced. Many current designs provide moving compression surfaces and bypass flow systems which, in general, increase airframe complexity, add considerable dry weight, and present difficult control problems. Less complex solutions to the matching problem are desirable.

One method whereby engine-inlet airflow matching may be achieved with reduced mechanical complication is to utilize the principle of heat exchange in the subsonic diffuser of the air-induction system. Since the relation between the aerodynamic and mechanical rotative speeds of a turbojet engine is varied by changing the inlet airflow temperature, either evaporative cooling or heat transfer from the internal airstream ahead of the engine may be utilized to maintain this relation constant over a wide airspeed range. References 1 and 2 propose employing this principle at subsonic and supersonic speeds to achieve thrust augmentation. The merits of the system for supersonic engine-inlet airflow matching, as well as thrust augmentation, appear considerable; and a comparative study with existing fixed- and variable-geometry inlets was therefore undertaken.

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Analysis of water injection in a typical supersonic inlet of a current turbojet engine was performed for Mach numbers up to 2.6 and altitudes up to 55,000 feet. Inlet airflow variation with various liquid-air ratios was established from one-dimensional analysis for complete evaporation in a constant-area stream, and the effect on engine-inlet matching was evaluated in terms of comparative net propulsive thrust and total liquid specific impulse. The expected improvement in maximum altitude was also determined.

METHODS OF ANALYSIS

The symbols employed in the analysis are listed in appendix A.

The basic system analyzed is shown schematically in figure 1. It consists of an axially symmetric nacelle with a 25° half-angle conical spike, a turbojet engine with afterburner, and a fully expanded exhaust nozzle. Representative on-design fixed-inlet performance was assumed to $M_0 = 2.0$, and above this value the performance of a fixed inlet designed for $M_0 = 2$ was assumed. To this basic system was added (for analysis) evaporation water cooling in the subsonic diffuser between stations 1 and 2. Also analyzed for comparative purposes was the basic system with first a bypass added for matching the airflows and then a translating spike.

For the case of water injection in the diffuser, one-dimensional water injection and evaporation were assumed between stations 1 and 2. The one-dimensional analysis for complete evaporation is presented in appendix B, and the results of this analysis are plotted on figure 2.

The method of engine-inlet airflow matching with water injection is somewhat different than the conventionally used technique and is discussed in appendix C.

The performance comparison between inlets is based on changes in net propulsive thrust, total liquid consumption, specific impulse, and increases in maximum altitude of a typical vehicle on which these inlets may be used. The net propulsive thrust F_n was computed by the method outlined in reference 3. Pumping data for a typical current high-speed turbojet engine were assumed, and the actual rise in total pressure due to water injection for computing thrust was neglected so that the answers are somewhat conservative. Both the afterburner total-pressure ratio and the combustion efficiency were maintained at 0.90. For complete afterburning, an exhaust temperature of 3200° R was assumed. (To provide a more realistic performance comparison, partial afterburning and also no afterburning were assumed for some flight conditions.)

In evaluating the aerodynamic drag forces on the nacelle system, only the spillage drag in the propulsive thrust parameter $F_n - D_s$ was considered. Thus, D_s is defined as the drag force on the nacelle at the operating point being considered minus the basic drag force at critical inlet flow for the same flight condition. For the bypass case, D_s represents the added drag due to bypassing the excess inlet airflow.

The specific liquid impulse is a measure of the efficiency of a propulsion system and is indicative of the airplane range possible with a given liquid load. For the water-injection case, the liquid consumption included both water and fuel. Without water injection, only fuel consumption is considered.

At cruise conditions for a given vehicle, an increase in engine thrust generally results not only in an increase in maximum speed but also raises the maximum altitude at which the vehicle can operate as well. Estimates were therefore made of the improvement possible over a fixed inlet at altitudes of 45,000 and 55,000 feet by utilizing bypass matching alone and the fixed inlet in combination with evaporative cooling as a matching technique. For simplicity only, the change in thrust was considered and no specific airplane configuration had to be assumed. The cruise drag of each configuration was taken equal to the net propulsive thrust of the fixed-geometry inlet system so that the increased altitude represents the higher altitude at which the bypass or the water-injection configuration could cruise at the same flight speed as the fixed inlet. Because a constant drag with altitude was assumed, such an estimate is quite conservative because of the reduction of the zero lift-drag force as compared with the increase in induced-drag force. Nevertheless, the trends thus obtained give a significant qualitative representation of the comparative capabilities of the inlet system being analyzed.

RESULTS AND DISCUSSION

The variation of the ratio of critical inlet airflow to engine corrected airflow with the basic fixed inlet is shown in figure 3 for a turbojet engine operating at constant maximum rotative speed. The inlet and engine were matched at $M_0 = 0.85$ with choking occurring in the minimum inlet area. Subsonic inlet performance was based on a pressure recovery of 0.95; supersonically the recovery included normal shock losses and 0.95 subsonic diffuser performance up to $M_0 = 1.35$. Above this speed representative fixed inlet data were used. The rapid increase of the inlet airflow with flight speed indicates the airflow spillage necessary to match the turbojet engine over the range of flight Mach numbers. At Mach 2.0, the spillage is about 50 percent of the total engine airflow. Although this appears to be a large excess airflow spillage requirement, this quantity still lies within the practical range of bypass and translating-compression-surface systems.

Matching the inlet and engine airflows by water injection, as previously mentioned, is discussed in appendix C. The result of applying this matching method to the engine airflow characteristic of the previous figure is indicated in figure 4. The net effect of reducing the temperature of the air ahead of the engine was to increase the engine corrected airflow and to reduce slightly the diffuser corrected airflow. Thus, the required airflow spillage (fig. 3) was reduced, and the inlet and engine airflow could be matched over the speed range from $M_0 = 1.5$ to 2.0 with less than a 3-percent liquid-air ratio (fig. 4). Therefore, this matching technique affords higher engine airflows and no additive drags so that the net propulsive thrust of the fixed inlet system is significantly improved.

In addition, for those current turbojet engines which are compressor-inlet total-temperature limited at about $M_0 = 2.0$ in the tropopause, water injection may be used to extend this speed range. Since the compressor-inlet temperature at the match point at $M_0 = 2.0$ (fig. 4) was considerably below the assumed limiting temperature, $T_0 = 706^{\circ}$ R, with water injection the flight speed was extended to the value which resulted in this compressor-inlet temperature. As seen in figure 4, the matched flight speed, based on engine limit at $M_0 = 2.0$ without water injection, can be increased over 25 percent without encountering airflow spillage at liquid-air ratios of only 3 to 5 percent. Although this is a significant increase in engine tolerance, airplane performance potential will probably be less because of the airplane drag rise with speed.

Inlets with water injection can be conveniently compared with other engine-inlet airflow matching techniques on a pod-nacelle propulsive-thrust basis. Such a comparison is made in figure 5. A fixed-geometry inlet designed for maximum M_0 of 2.0 has been used as the frame of reference, and the ordinate of figure 5 represents the relative propulsive thrust between it and the specific matching system being considered.

The variable-geometry inlets, bypass and translating spike, were sized at $M_0 = 0.85$ (altitude, 35,000 ft) and the bypass was designed for

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shock on cowl-lip performance at $M_0 = 2.0$. Although translating the spike at the sizing M_0 allowed a slightly smaller nacelle, the actual nacelle size was set by the engine-plus-accessory maximum cross-sectional area, which effectively resulted in three nacelles of the same size and about the same geometry. Since the effect of cowl pressure drag is not included in the net propulsive thrust analysis, the effect of a slightly smaller capture area for the translating-spike inlet is neglected. The data were selected for inlets having the same cowl-lip slope, and the bypass discharge angle was such as to allow approximately axial discharge of the spilled airflow.

The large thrust augmentation characteristics of the water-injection system are immediately apparent from the comparison presented in figure 5. The translating-spike and the bypass inlet (which have comparable performance) achieve only about one-half the thrust augmentation level of the liquid-injection inlet. For the range of Mach numbers between 1.5 and 2.0, the propulsive thrust of the water-injection system is from 17 to 56 percent higher than that of the best performing variable-geometry inlet and from 20 to 130 percent higher than the thrust of the fixed inlet. These large thrust increases resulted chiefly from increased engine airflows and engine pressure ratio and provide considerable margin for improved airplane speed, maneuverability, acceleration, and altitude.

Above Mach 2.0 (where the data are based on the fixed-geometry-inlet cruise thrust at Mach 2.0), the water-configuration thrust drops off rapidly with increased Mach number because of increased inlet total-pressure losses at off-design inlet operation. The bypass and translating-spike inlets terminate at Mach 2.0 because the assumed inlet temperature limitation (on the turbojet engine) occurs at this speed.

Although water injection increased the propulsive thrust of the configuration considered, it did so at the expense of an increase in the liquid flow rate; for both fuel and water are being consumed. The volume and weight of the water required necessarily replace fuel load and reduce total endurance time below that of the basic fixed-geometry inlet configuration. In order to evaluate this added liquid consumption and determine its over-all effect on vehicle performance, the specific liquid impulse ((lb thrust/(lb liquid consumed)(sec)) was computed for the water-injection and bypass cases and compared with that of the basic fixed-geometry inlet. These results are presented in the lower half of figure 6.

On the basis described, the bypass inlet displayed the best impulse performance over the entire speed range. Assuming complete evaporation, the specific impulse of the water-injection configuration was only approximately 90 percent of the value obtainable with the basic fixed-geometry inlet. The bypass configuration, on the other hand, gave a specific impulse equal to that of the basic fixed-geometry configuration at Mach 1.5 and a value 35 percent greater at Mach 2.0.

Careful examination reveals, however, that such a comparison is quite unrealistic, for the comparison at each Mach number is being made at unequal thrust levels between configurations. As indicated in figure 5, the propulsive thrust level with water injection is considerably greater than that for the bypass configuration. An additional comparison at equal thrust levels was, therefore, also made by assuming reduced fuel flow and partial afterburning for the water-injection case to reduce its thrust first to the level of the basic fixed-geometry configuration and then to the level of the bypass configuration.

On this basis the impulse of the water-injection configuration may be improved about 10 percent for most of the Mach number range. Although only comparison with the fixed-geometry thrust level is shown, the performance at the bypass thrust level is about the same except at Mach 2.0, where the impulse is 10 percent greater. The rapid impulse decrease above Mach 1.8 for the comparison with the fixed-inlet case is attributed to changing the engine operating match point.

To demonstrate the influence evaporation effectiveness has upon the specific impulse, the variation for no evaporation and no thrust augmentation is also included in the lower half of figure 6. The region bounded by the upper and lower curves for complete and no evaporation represents the range of practical impulses attainable in an airplane installation. The degree of evaporation achievable in a practical installation was not considered herein.

Included in the upper half of figure 6 is the variation in total liquid consumed by the various matching systems under consideration. Again the basic fixed-geometry inlet is used as a basis for comparison. Over the Mach number range from 1.5 to 2.0, the water-injection system progressively consumes from 25 to 240 percent more liquid than either the bypass or fixed-geometry systems. The bypass and fixed-geometry configurations have about equal liquid consumption because their pressure recoveries are nearly the same.

On the basis of equal propulsive thrust levels, the water-injection matching technique compares considerably more favorably. Essentially, the same total liquid consumption results with either the water-injection or the basic fixed-geometry inlet and at Mach 2.0 is only 56 percent greater for the water-injection system than for the bypass system.

The liquid consumption indicated in figure 6 does not reflect the relative changes in fuel flow necessary to operate the engine at partial afterburning. No data are presented for these changes; however, it was found that for the case of complete evaporation (full afterburning) the fuel flow increased from 13 to 50 percent. However, at equivalent thrust levels (or partial afterburning) the fuel consumed with water injection was from 20 to 60 percent of that of the bypass inlet and 16 to 40 percent of that of the fixed inlet.

Because the water-injection system has demonstrated thrust capabilities above and considerably beyond those of the bypass, translating-spike, and fixed inlets, it affords reserve power to increase vehicle flight altitude over that possible with other inlet matching systems. A comparison between the bypass and water-injection systems based upon percentage of altitude increase over the basic fixed-geometry inlet is presented in figure 7. Water injection increased the fixed-inlet cruise altitude from about 8 to 35 percent at 45,000 feet and from 5 to 22 percent at 55,000 feet. At both altitudes, the percentage of altitude improvement with the bypass inlet was about one-half of that obtained by the water-injection system.

It is apparent that the use of water injection for engine-inlet matching provides an adequate means for improving engine-inlet airflow compatibility with simultaneous thrust augmentation. Although the liquid quantities consumed by such a system are large compared with those of other matching techniques, use of water injection in combination with another matching technique such as a bypass may be desirable to take advantage of the short-term thrust augmentation of the former. Consideration should be given to using water injection in order to provide added facility for maneuvering, acceleration, and increased altitude for aircraft currently utilizing variable-geometry schemes for engine-inlet matching. If endurance time can be compromised, water injection may also serve as a less mechanically complex system for engine-inlet matching.

SUMMARY OF RESULTS

An analysis of engine-inlet matching by means of evaporation cooling due to water injection in the subsonic diffuser of a supersonic propulsion system indicated the following results:

1. Engine-inlet airflow matching was achieved over Mach numbers of 1.5 to 2.0 with no spillage and liquid-air ratios up to 0.03. Associated net propulsive thrusts were 17 to 56 percent greater than that of the best performing variable-geometry inlet.

2. For a typical turbojet engine with the compressor-inlet temperature limited at Mach 2.0, the maximum permissible flight speed was increased 25 percent without spillage.

3. Specific liquid impulses of the water-injection system were considerably lower than that of a bypass inlet and were about equal to that of a fixed-geometry inlet without water injection. The total liquid consumed by the water-injection system, at matching for Mach 2.0, was 240 percent as much as that of the bypass inlet. However, at equal thrust levels, the total liquid consumed was only 56 percent greater than that of the bypass-system value.

4. The large absolute thrust gains due to water injection increased the cruise altitude of a vehicle using a bypass inlet from 55,000 to 60,000 feet and for a fixed inlet system from 55,000 to 67,000 feet at a free-stream Mach number of 2.0.

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APPENDIX A

SYMBOLS

A	area, sq ft
A_*	choked area
c_p	specific heat at constant pressure, 0.241 for air and 0.448 for water vapor at low pressure, Btu/(lb)($^{\circ}$R)
c_v	specific heat at constant volume, 0.172 for air and 0.337 for water vapor at low pressure, Btu/(lb)($^{\circ}$R)
D	drag, lb
F	thrust, lb
H_v	latent heat of vaporization, Btu/lb
h	altitude, ft
Δh	altitude increment, ft
h_l	liquid enthalpy, Btu/lb
h_v	vapor enthalpy, Btu/lb
I	specific impulse, $(F_n - D_s)/w_f$ or $(F_n - D_s)/(w_f + w_l)$, sec
M	Mach number
m	molecular weight
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
Q	heat transferred, Btu/sec
R	gas constant, ft-lb/(lb)($^{\circ}$R)
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
w	weight flow rate, lb/sec

$\frac{w\sqrt{\theta}}{\delta A}$	corrected weight flow ratio per unit area, lb/(sq ft)(sec)
γ	ratio of specific heats, 1.4 for air
δ	generalized correction parameter, $P/2116$
$\sqrt{\theta}$	corrected temperature ratio, $\sqrt{T/519}$
ρ	density, lb/cu ft
ψ	relative humidity, $p_v/p_{s.v.}$

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Subscripts:

a	air
cr	cruise
crit	critical
e	engine
eff	effective
f	fuel flow
fg	fixed geometry
i	inlet
l	liquid
n	net
s	spillage
s.v.	saturated vapor
v	vapor
0	free-stream conditions
1	before evaporation
2	after evaporation
3	compressor inlet

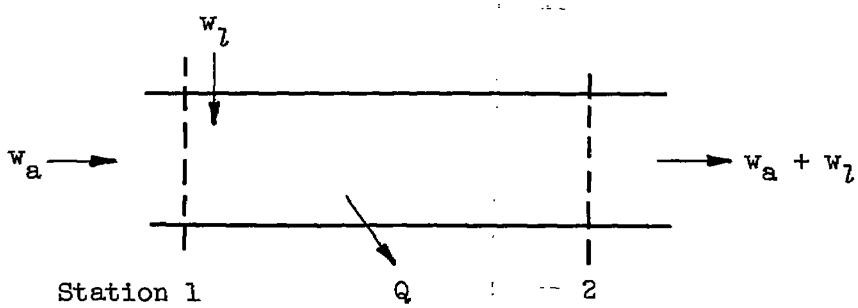
4 turbine outlet

5 exhaust nozzle

APPENDIX B

CALCULATION OF ONE-DIMENSIONAL FLOW WITH COMPLETE EVAPORATION OF WATER IN A CONSTANT-AREA CHANNEL

In order to evaluate the effect of cooling a subsonic stream by evaporation in a constant-area channel, as shown in the following sketch, the following assumptions were made: 4158



(1) Frictionless flow from station 1 to 2.

(2) Complete evaporation of liquid between stations 1 and 2.

(3) $t_v = t_2$.

(4) $Q = 0$.

(5) $H_v = H_v(t_{1,l})$.

(6) Fluid is perfect gas before and after water evaporation.

(7) Variation of the specific heat with temperature of the mixture during evaporation is small and is therefore neglected.

The mass flow continuity between stations 1 and 2 is

$$w_2 = w_a\left(1 + \frac{w_l}{w_a}\right) \tag{B1}$$

and

$$w_1 = w_a$$

where all subsequent subscripts a are used interchangeably with station 1. Assuming that the liquid is injected normal to the streamwise direction, the momentum equation is

$$\frac{p_1}{p_2} = \frac{1 + \gamma_2 M_2^2}{1 + \gamma_a M_1^2} \tag{B2}$$

Rewriting, in terms of total temperature before and after evaporation, equations (B1), (B2), and the equation of state $p = \rho R t$ gives

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$$\sqrt{\frac{T_2}{T_1}} = \frac{\varphi_1}{\varphi_2} \frac{1}{\left(1 + \frac{w_l}{w_a}\right)} \sqrt{\frac{\gamma_2 R_a}{\gamma_a R_2}} \tag{B3}$$

where

$$\varphi = \frac{1 + \gamma M^2}{M\sqrt{1 + \frac{\gamma - 1}{2} M^2}}$$

γ_2 can be found from reference 4 as

$$\gamma_2 = \gamma_a \left(\frac{1 + \frac{w_l}{w_a} \frac{c_{p,v}}{c_{p,a}}}{1 + \frac{w_l}{w_a} \frac{c_{v,v}}{c_{v,a}}}\right)$$

and the gas constant R_2 for the mixture is

$$R_2 = \frac{R_a + \left(\frac{w_l}{w_a}\right) R_v}{1 + \left(\frac{w_l}{w_a}\right)}$$

In order to obtain T_2 in equation (B3), the energy equation per pound of dry air at station 1 and the water-vapor - air mixture at station 2 may be written as

$$c_{p,a}T_a + \frac{w_l}{w_a} h_l(t_{1,l}) = \frac{w_l}{w_a} h_v(t_2) + c_{p,a}T_2 + \frac{w_l}{w_a} c_{p,v}T_2 - \frac{w_l}{w_a} c_{p,v}\left(\frac{t_2}{t_{1,l}}\right) t_{1,l}$$

where the vapor velocity is assumed equal to the air velocity at station 2. By rearranging terms and partially accounting for the vapor velocity at station 2 by assuming that $t_2 = t_{1,l}$ (in case of the final term only), the energy equation becomes

$$T_2 = \frac{T_1 - \frac{w_l}{w_a}\frac{1}{c_{p,a}}\left[H_v(t_{1,l}) - c_{p,v}t_{1,l}\right]}{\left(1 + \frac{w_l}{w_a}\frac{c_{p,v}}{c_{p,a}}\right)} \tag{B4}$$

Therefore, by using equations (B3) and (B4) and selecting values for T_1, M_1, and w_l/w_a, M_2 and the corresponding corrected airflow 4158

$$\left(\frac{w\sqrt{\theta}}{\delta A}\right)_2 = \frac{526\sqrt{\frac{\gamma_2}{R_2}}}{\left(\frac{\gamma_2 + 1}{2}\right)^{\frac{\gamma_2+1}{2(\gamma_2-1)}}}\left(\frac{A_*}{A}\right)_{\gamma_2,M_2}$$

may be found by using

$$t_{1,l} = 59^{\circ}\ F$$

$$\gamma_a = 1.4$$

$$\gamma_v = 1.33$$

$$\frac{R_a}{R_v} = \frac{m_v}{m_a} = 0.622$$

and

$$m_a = 29$$

Results of these calculations are presented in nondimensional form in figure 2.

The relative humidity of the air at station 2 is found by using the equation of state $p = \rho Rt$, Dalton's law of partial pressures $p_2 = p_a + p_v$, and the expression for mass flow. By combining these expressions, the relative humidity may be expressed as a function of altitude, free-stream Mach number, inlet Mach number, pressure recovery, liquid-air ratio, and the Mach number after evaporation:

$$\psi = \left(\frac{\frac{w_l}{w_a}\frac{R_v}{R_a}}{1 + \frac{w_l}{w_a}\frac{R_v}{R_a}}\right)\left(\frac{1 + \gamma_a M_1^2}{1 + \gamma_2 M_2^2}\right)\left(\frac{p}{P}\right)_1 \frac{P_1}{P_0}\left(\frac{P}{p}\right)_0 \frac{p_0}{p_{s.v.}} \tag{B5}$$

Since $p_{s.v.} = p(t_2)$ and since all the other conditions are known, or can be found, the relative humidity for a given inlet operating condition is obtainable.

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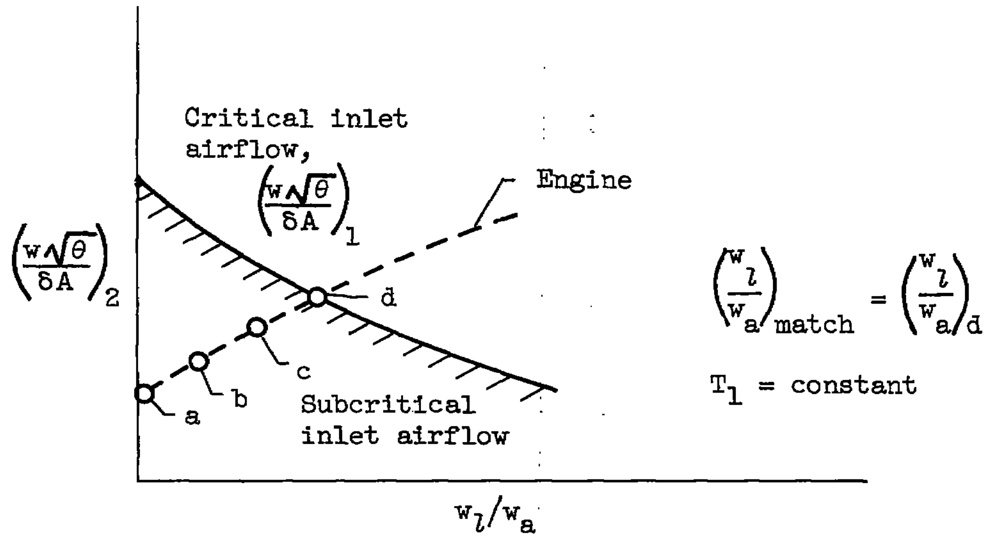
APPENDIX C

ENGINE-INLET MATCHING WITH EVAPORATIVE COOLING

AHEAD OF THE TURBOJET ENGINE



A graphical method was used for obtaining a simultaneous solution to the engine-inlet matching problem with evaporation cooling. The preceding sketch represents a cross plot of figure 2 for the given initial corrected airflow and for a given Mach number in the tropopause. The solid curve represents the critical inlet airflow behind the terminal shock and ahead of the liquid-injection section (see fig. 1) in the diffuser. Because the inlet airflow is larger than the required engine airflow at supersonic speeds (fig. 3), the excess must be spilled ahead of the inlet cowl with resulting high drags. Without such spillage the inlet and engine could be considered as being matched. However, spillage does exist in this case, and it may be considered as the margin of "mismatch" between the inlet capacity and the engine requirement. Since the inlet and engine are mismatched by about 50 percent at Mach 2.0, for example, the inlet corrected airflow for this condition is less than the critical inlet flow and is represented by point a. If a liquid-air ratio $(w_l/w_a)_b$ less than the matched liquid-air ratio $(w_l/w_a)_d$ is selected, T_2 can be computed from equation (B4). This gives the effective engine operating temperature whereby the corrected engine airflow can be found:

$$\left(\frac{w\sqrt{\theta}}{\delta A}\right)_{2,b} = \left(\frac{w\sqrt{\theta}}{\delta}\right)_{T_{eff,b}} \left(\frac{\delta_{eff}}{\delta_2}\right) \frac{1}{A_2}$$

where

$$\frac{\delta_{eff}}{\delta_2} = 1.0$$

Point b is still subcritical. However, increased amounts of liquid injection $(w_l/w_a)_c$ and $(w_l/w_a)_d$ result in the curve abcd and establish the matched liquid-air ratio $(w_l/w_a)_d$ at which the inlet operates without spillage. From the sketch it is easily seen how the diffuser-discharge corrected airflow is reduced and the engine corrected airflow is increased as the liquid-air ratio is increased.

In order to restrict relative humidities to unity at station 2, equation (B5) was used to determine the value at the successive points a, b, and c. No conditions with relative humidities greater than unity were considered and were not required to achieve the match point.

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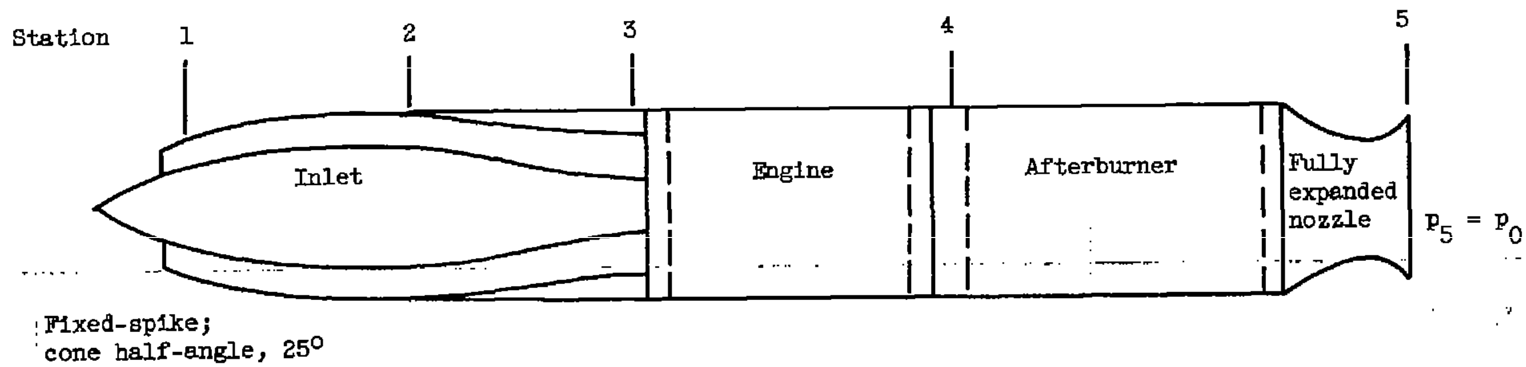
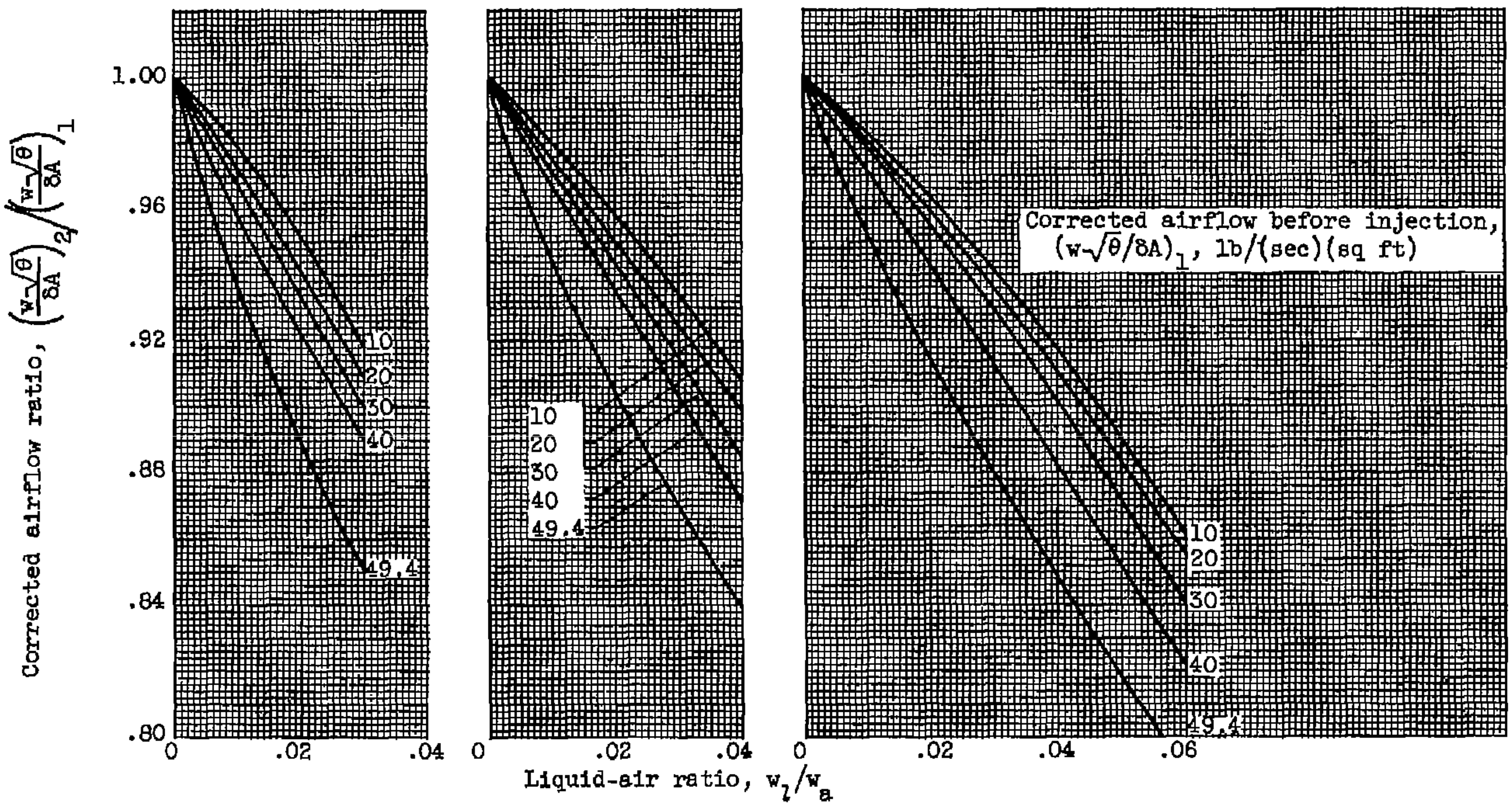


Figure 1. - Schematic diagram of supersonic propulsion system.

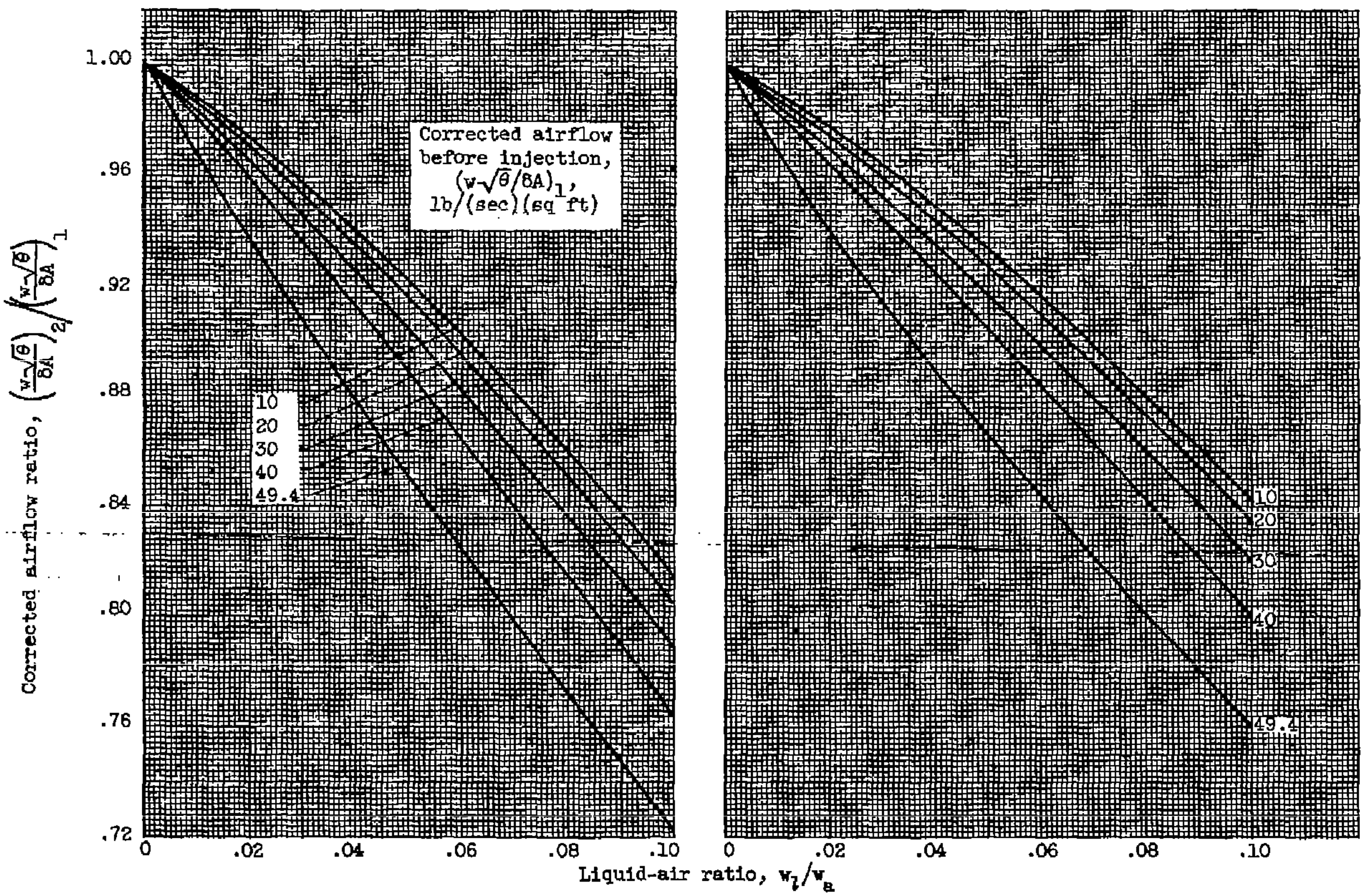


(a) Temperature before evaporation, 570° R.

(b) Temperature before evaporation, 648° R.

(c) Temperature before evaporation, 706° R.

Figure 2. - Variation of corrected airflow ratio before and after liquid injection with liquid-air ratio.



(d) Temperature before evaporation, 884° R.

(e) Temperature before evaporation, 999° R.

Figure 2. - Concluded. Variation of corrected airflow ratio before and after liquid injection with liquid-air ratio.

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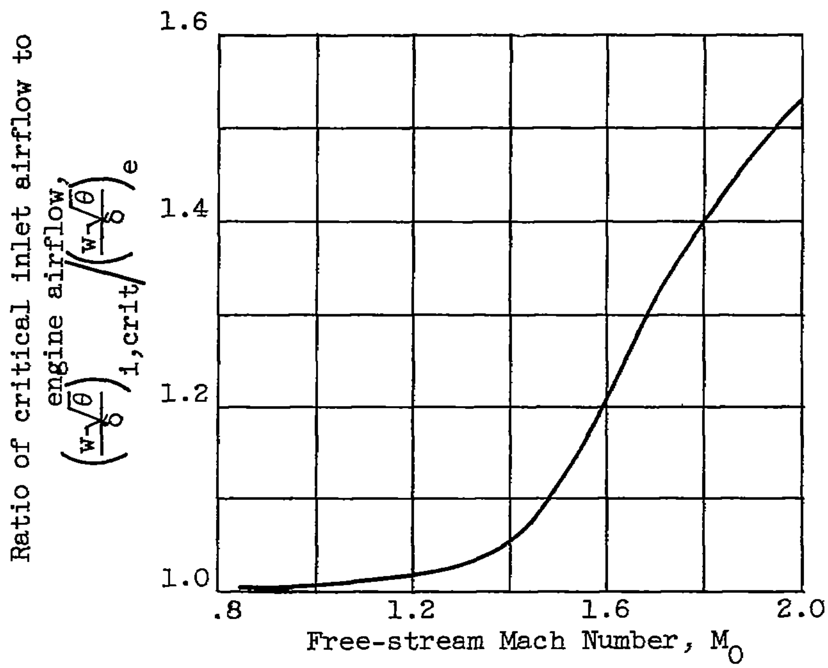

Figure 3. - Variation of ratio of critical inlet airflow to engine airflow with free-stream Mach number. Altitude, 35,000 feet and above.

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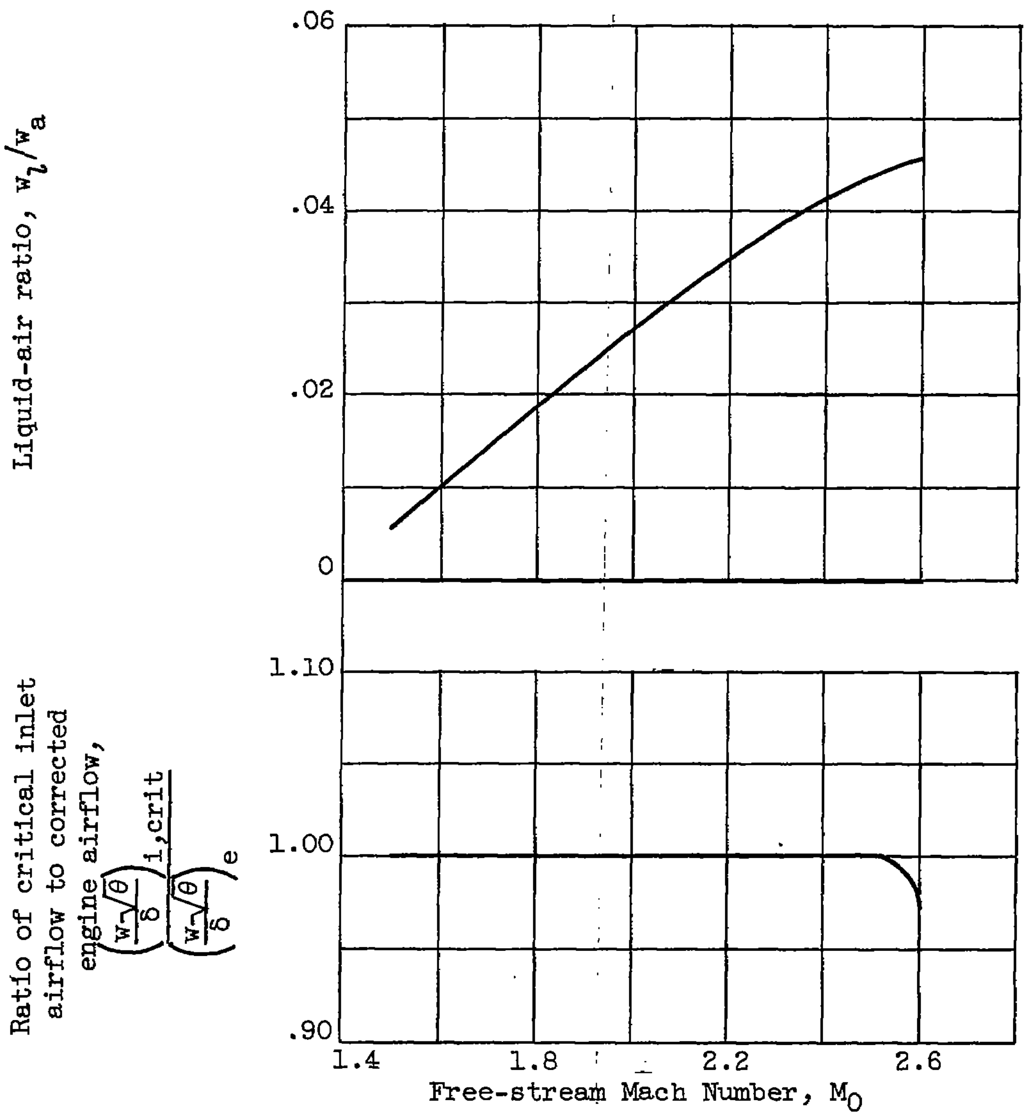

Figure 4. - Variation of matched liquid-air ratio and matched engine-inlet airflow ratio with Mach number. Altitude, 35,000 feet.

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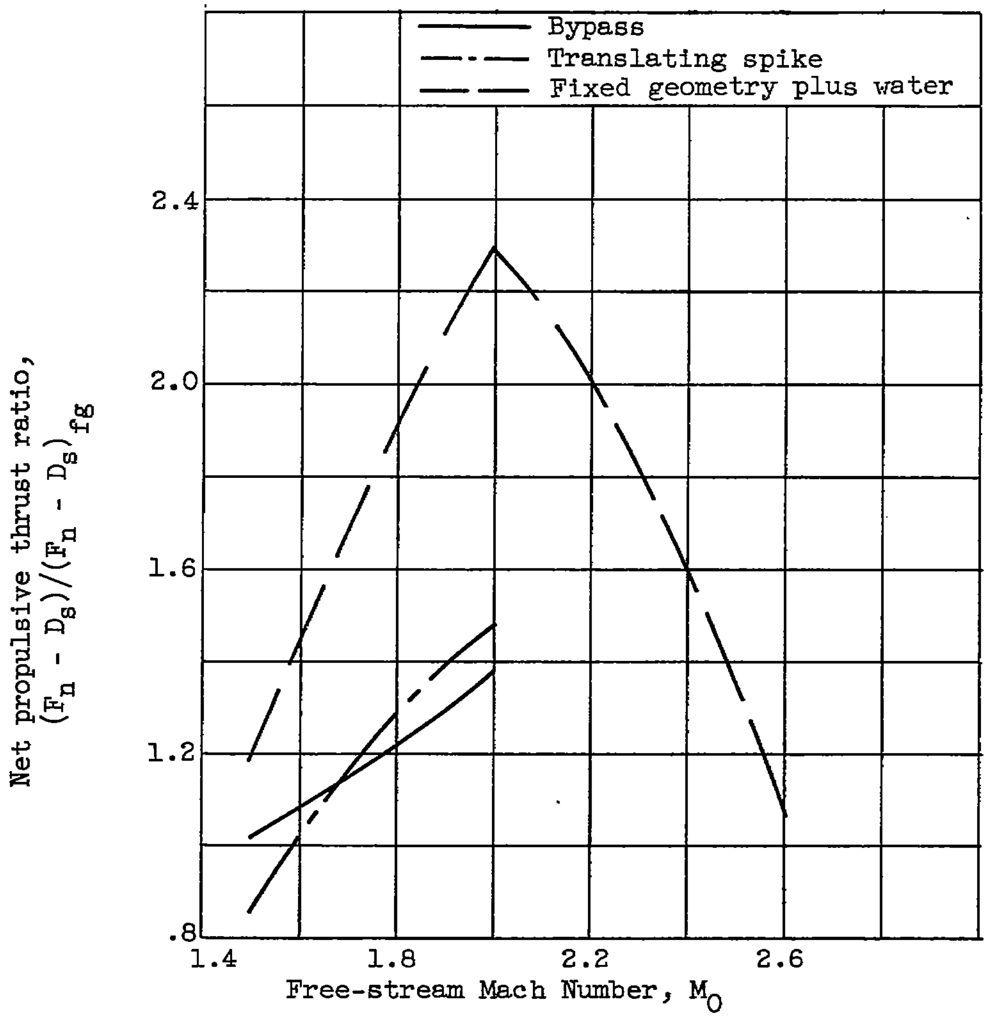

Figure 5. - Comparison of net propulsive thrust ratios. Altitude, 35,000 feet.

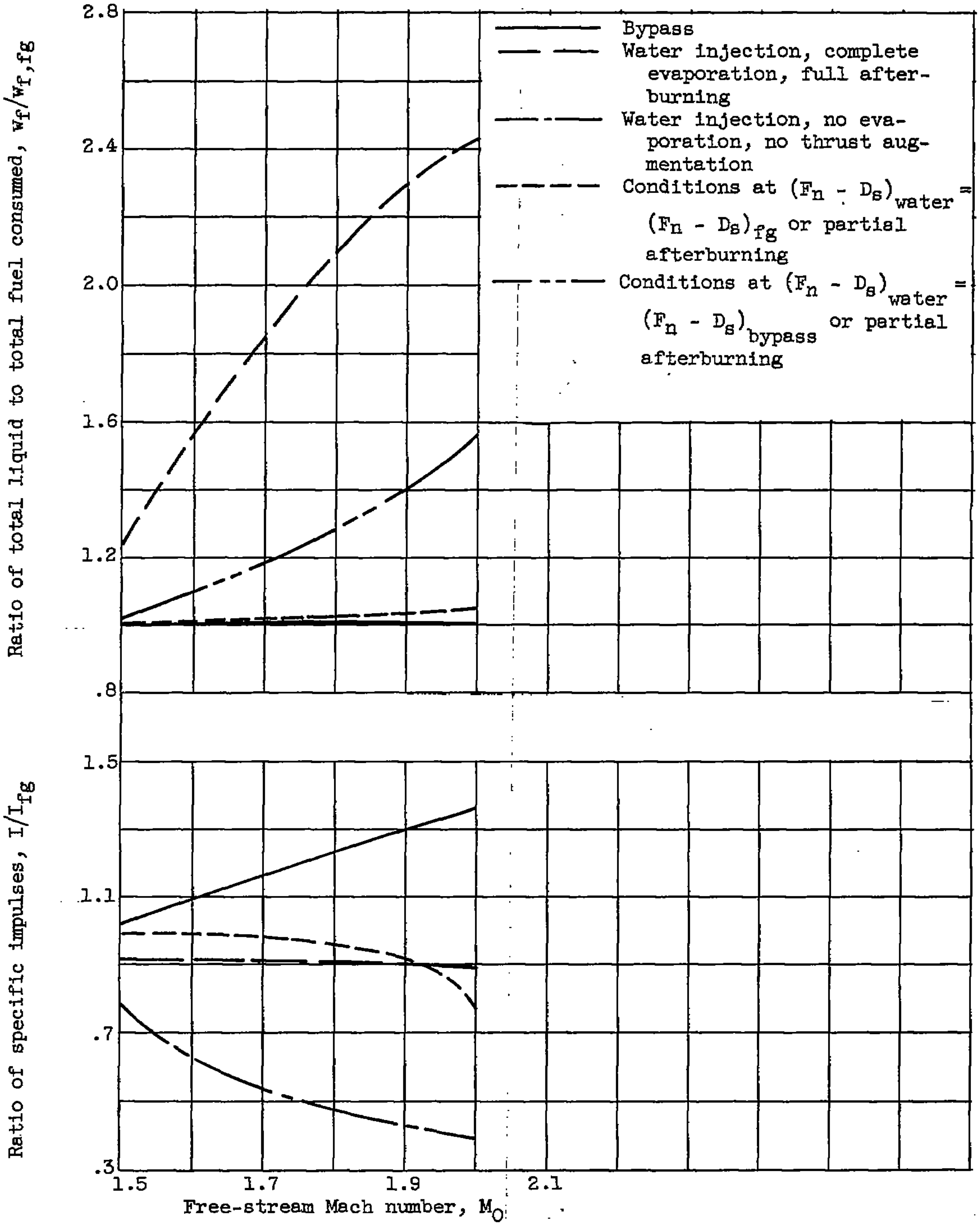

Figure 6. - Variation of liquid and impulse ratios with free-stream Mach number. Altitude, 35,000 feet.

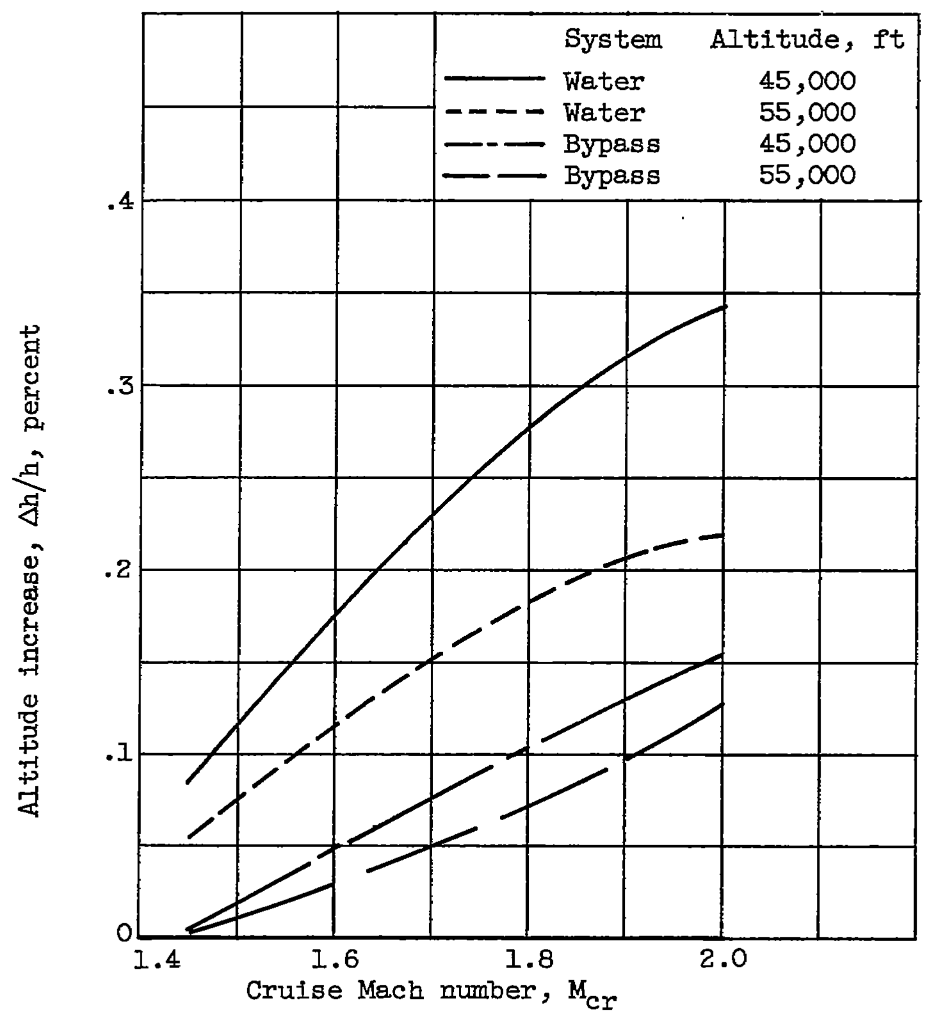

Figure 7. - Percentage of altitude increase (based on fixed-geometry inlet) for variable-geometry and water-injection inlets.